Laser Guiding and Wakefield Acceleration In Plasmas

Cameron Geddes
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Physics Department Qualifying exams

Work in collaboration with:

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Laser pulse in a plasma excites a wake field

An intense laser pulse of length L~$\square$p/2 = $\square$c/$\square_p$ in a plasma excites a copropagating electron plasma wave -> laser wakefield

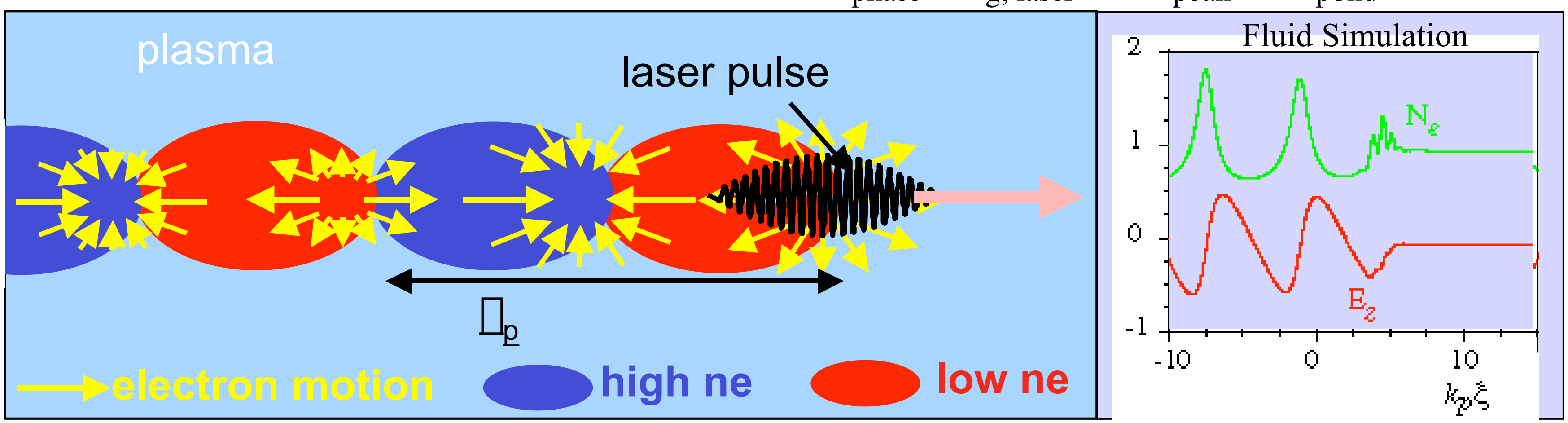
-electrons are ejected from a intense pulse by pondermotive pressure

$V_{pond}=mc^2a_o{}^2/4e$ where $a_o = eE/\square mc$

resulting from oscillation of the electrons in the spatially varying laser field

-in the wake of the pulse electrons rush back in a time $\square/\square_p$

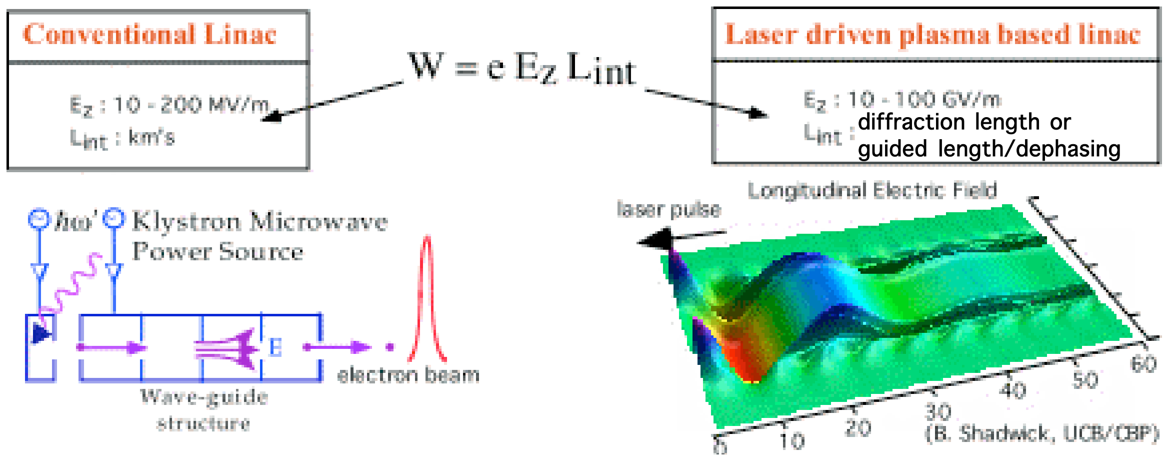
-if pulse length is matched to this time, an electron plasma wave follows in the wake of the pulse with $v_{phase}= v_{g,\ laser}$ & $\square_{peak} \sim V_{pond}$



-Linear regime is ~ sinusoidal: density depletion and $n_{e,min}$ -> 0 distorts

Longer pulses can self modulate at $\square_p$ and also self guide -> simple accelerator but without control.

Laser driven plasma based linacs offer high gradients

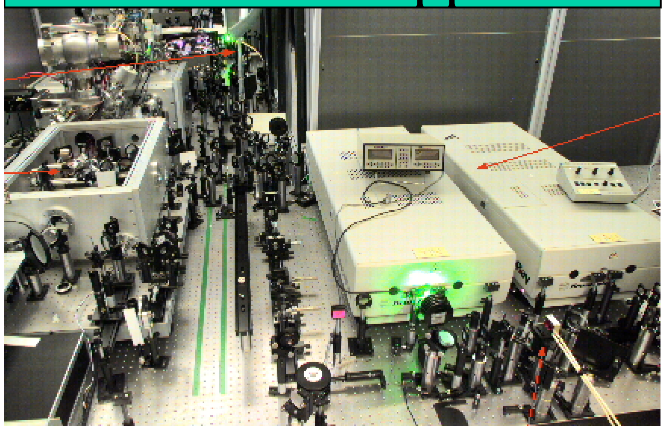


- Plasma wave excitation using high intensity multi TW laser pulses offers
  - High gradient: limited by wavebreaking $eE/m\omega \sim \omega/k$. ~100GeV/m @ $10^{18}/cm^3$ (50fs)
  - Short wavelength structure $\lambda_p = 2\pi c/\omega_p \sim 40\mu m$ @ $10^{18}/cm^3$
  - High phase velocity ~ $\gamma_{g,laser} = \omega_p/\omega = 50$ @ $10^{18}/cm^3$
- Key issues:
  - Production of wakes, acceleration, optimization
  - Injection of electrons
  - Laser guiding: extend acceleration length beyond diffraction
  - Coupling to structure & Dephasing - control of density & gradient
  - Staging

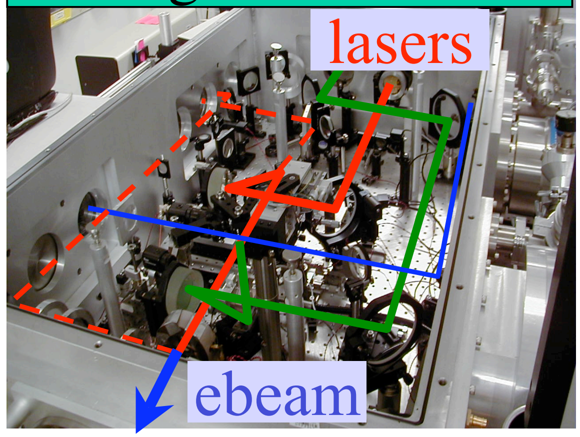
Laser driven accelerator R&D at l'OASIS lab

- Test bed for R&D concepts towards 1 GeV module of a laser accelerator
- Facility includes 10 TW, 50 fs laser system @ 10 Hz (100 TW under development)
- Comprehensive diagnostics & control systems

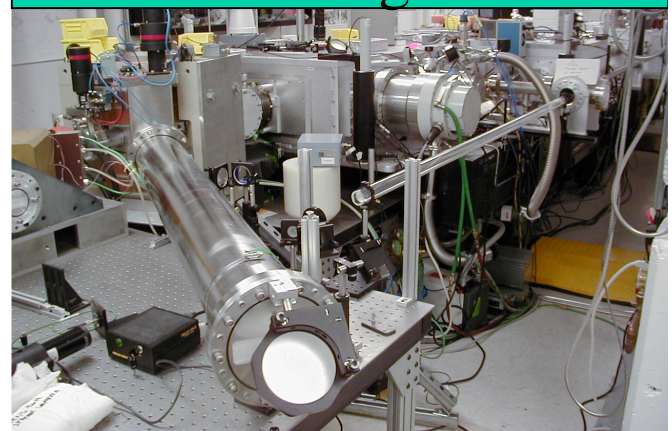
10 TW Ti:sapphire



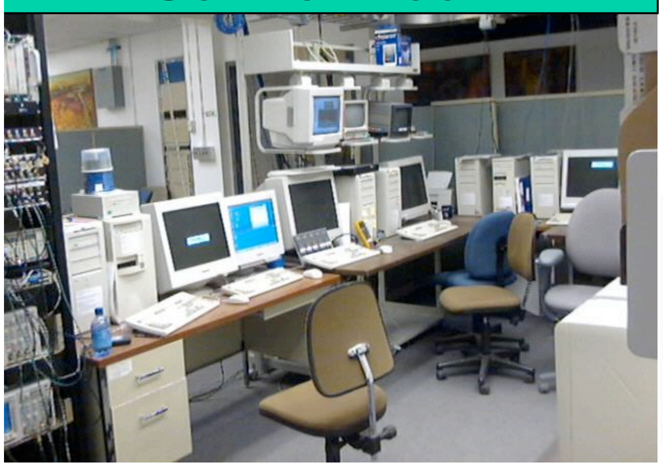
Target Chamber

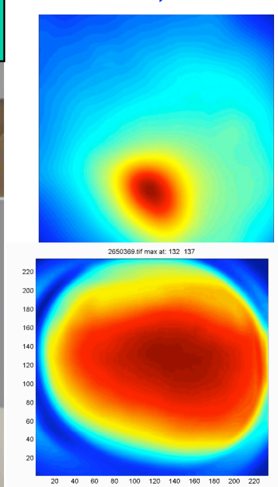


Shielded target room



Control Room





High energy
< 10 mrad

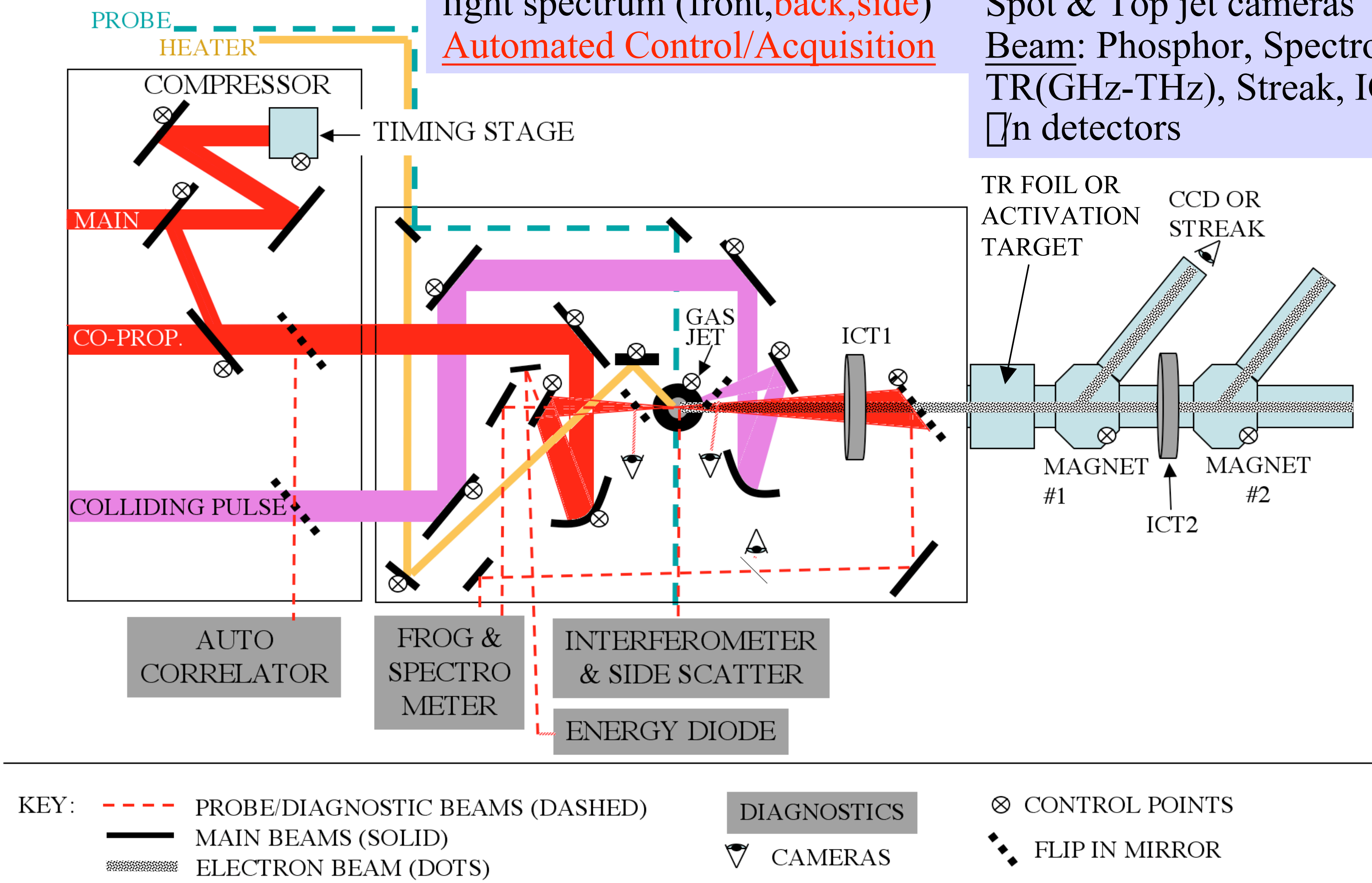
Low energy
100 mrad

100 TW Ti:sapphire
Under construction

Comprehensive Diagnostics & Controls Available For Wakefield Experiments

Plasma: Interferometer, Scattered light spectrum (front,back,side)
Automated Control/Acquisition

Laser: FROG, SSA, Diodes, Spot & Top jet cameras
Beam: Phosphor, Spectrometer, TR(GHz-THz), Streak, ICT, □/n detectors



Thesis Topic: Laser Guiding and Wakefield Acceleration in Plasmas

•Experimental study of wakefield acceleration focusing on the effects of laser guiding, electron injection, and plasma tuning.

-First guiding of acceleration relevant intensities (>10^{18}W/cm^2) over many Z_R

-Demonstration of controlled injection into wakefield accelerator

-Characterization of plasma effects on acceleration

•Preliminary and development experiments (in progress)

-Self modulated laser wake field (SMLWFA) experiments

Leemans et al, PRL 2002 ; Leemans et al., Phys. Plasmas 2001

-Gas target modeling and development

-Laser, Control and diagnostic development

Geddes et al, Proceedings of AAC 2002 ; Leemans et al., Phys. Plasmas 2001

•Main experiments (beginning fall 02)

-Laser guiding via plasma channel @ I > 10^{18}W/cm^2

Volfbeyn et al, Phys. Plasmas 1999

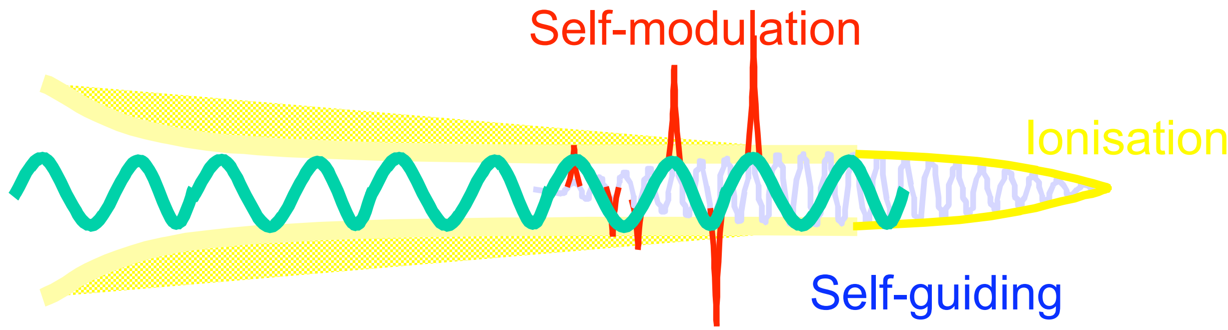
-Controlled injection & Guiding in standard wakefield (LWFA) experiments

Colliding pulse injection - Esarey et al, PRL 1997

SMLWFA Injectors - Reitsma et al, PRST-AB 2002

-Guided self modulated experiments

SM-LWFA experiments produce >1nC electron bunches with significant fraction at >25MeV



Self-modulation occurs when:
- Power > Critical power
- Laser pulse length >>Plasma period

Then

•Pulse self guides

•Pulse modulates into pulses @ ω_p

Currently Available:
- Power = 2.5 - 10 TW, pulse length = 60-15 μm

With plasma density n_e = 3e19cm^{-3} self modulation when:

• P > 1 TW

• Laser pulse length >> 6 μm = λ_p

Experiments scan:

•target density and position

•laser pulse length/chirp

Observe:
- Plasma density and profile
- Laser pulse shape
- Beam charge, collimation
- Beam energy from nuclear activation, magnetic spectrometer
- Transmitted light spectrum

Long pulses: Self Modulation & Guiding

-Pulses with L>λ_p are used for proof of principle experiments.

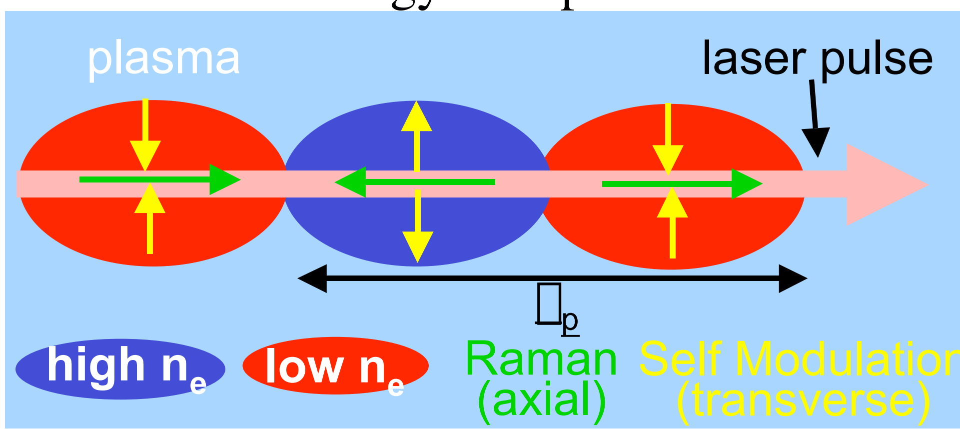
-Long pulses self guide due to relativistic variation in index of refraction:

$$\eta \approx 1 - \frac{\omega_p^2}{2\gamma_\perp \omega^2} = 1 - \frac{\omega_p^2}{2\omega^2}(1+a^2)^{-1/2}$$

if a is peaked on axis, this creates a guiding profile for $P \geq P_c[GW]=17(\omega/\omega_p)^2$

-Wake driven up from noise by forward Raman scattering(1d) and Self Modulation(2d).

Small initial perturbation -> energy transport & enhanced wake/ modulation



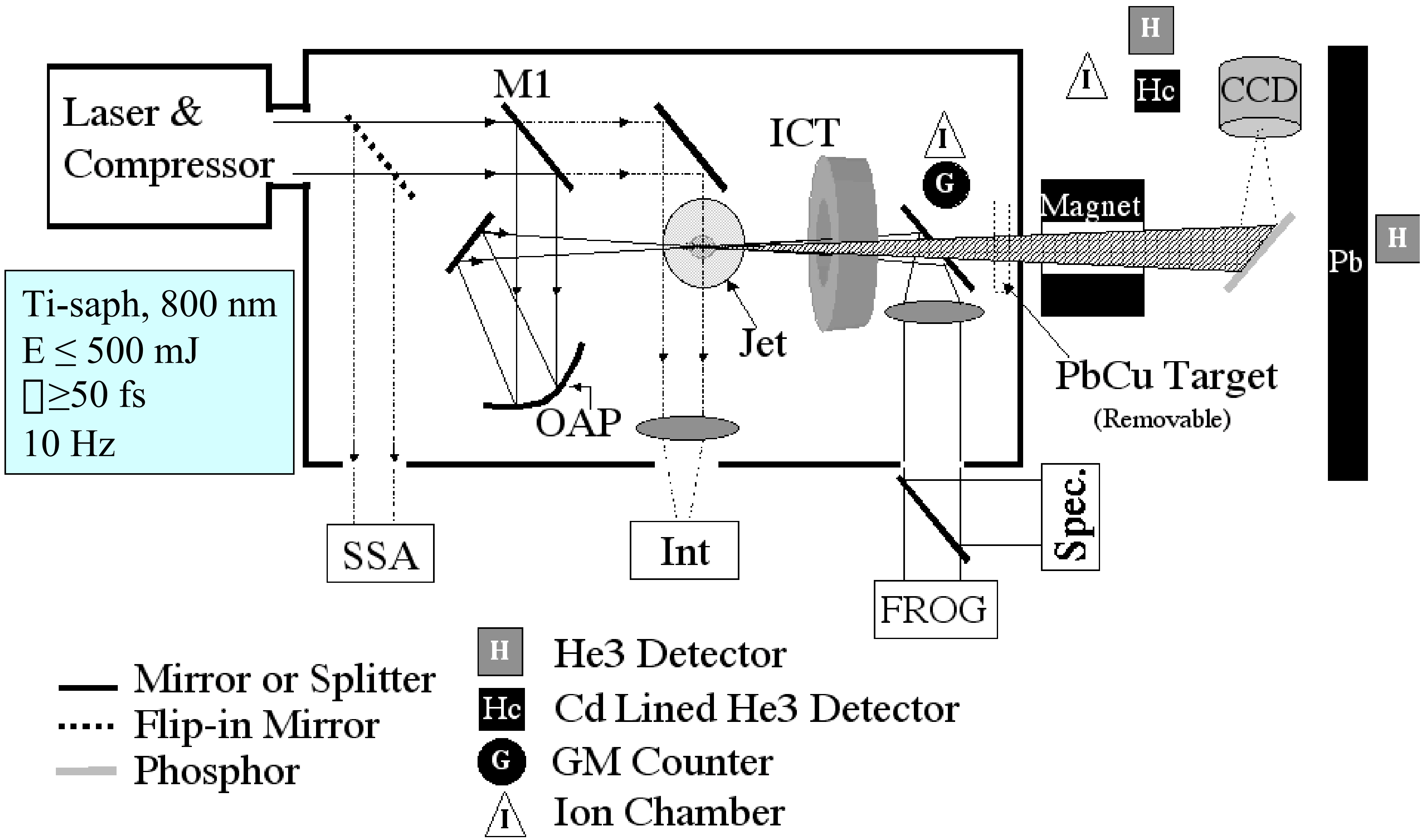
-Particles are trapped by Raman backscatter (slow beat wave) or wave breaking

-Simple, single beam experiment

-High charge due to high density

-Low energy due to low γ_g and 100% energy spread due to uncontrolled injection

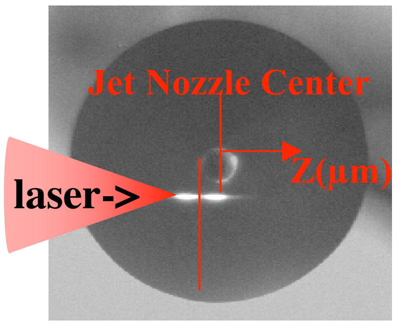
Experimental set-up at the 10 TW, 10 Hz l'OASIS laser

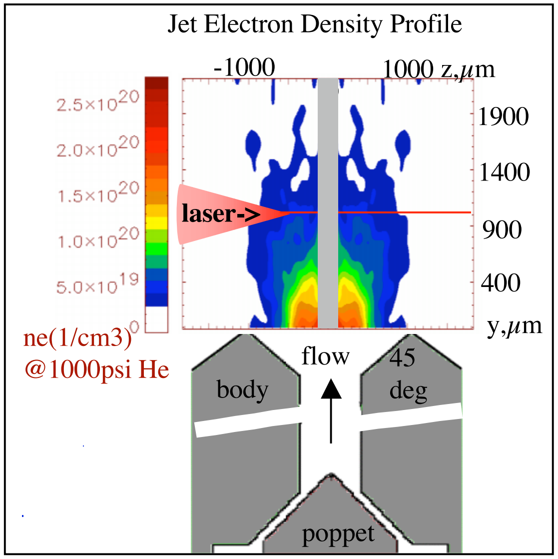


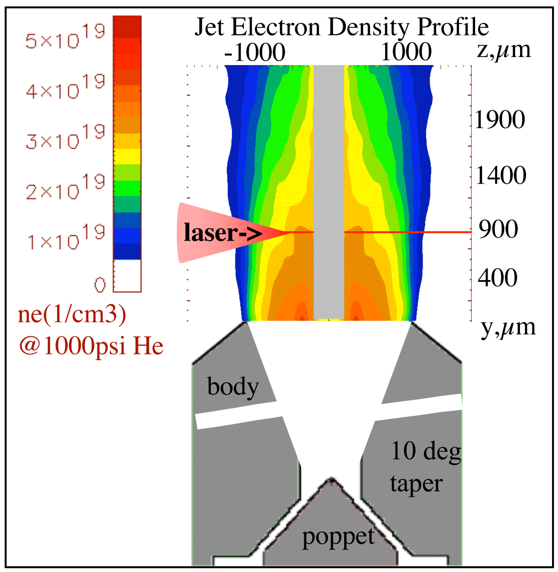
*W.P. Leemans et al., Phys. Plasmas 2001

Jet optimization is under way to control and enhance accelerator output

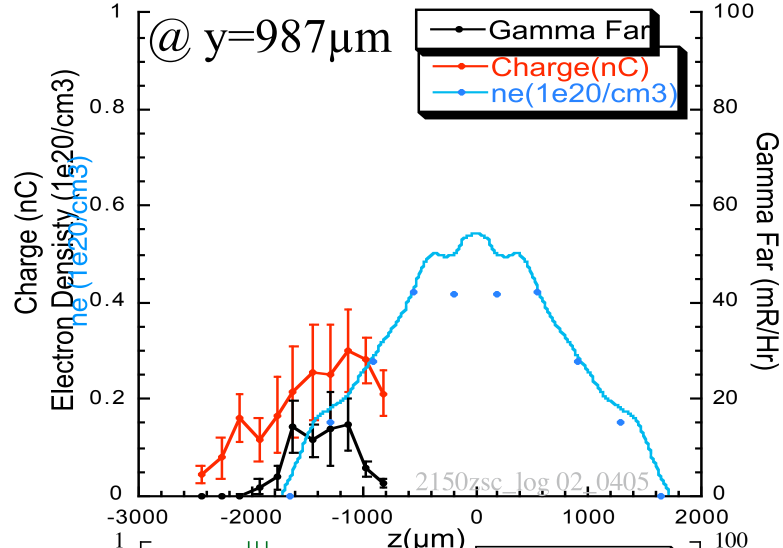
Top view of jet showing geometry

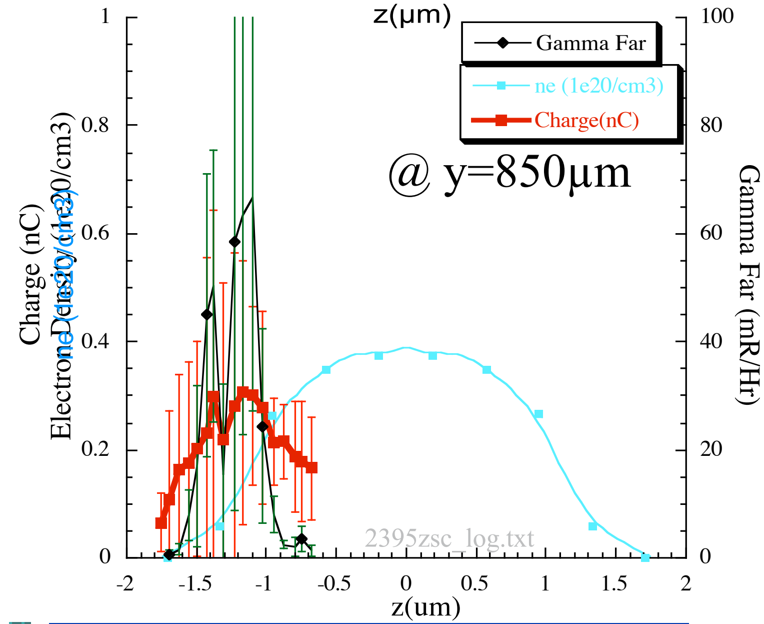




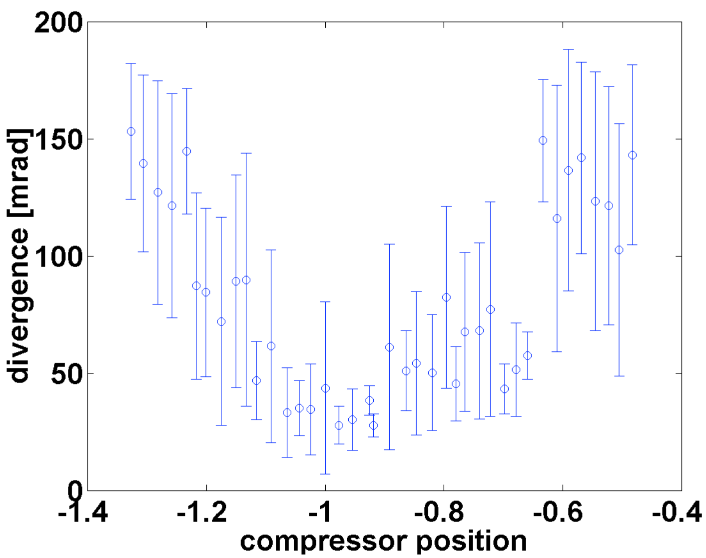


Yield vs. z

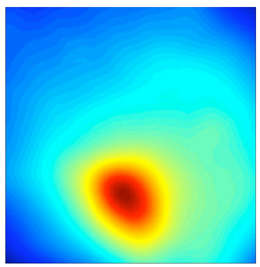




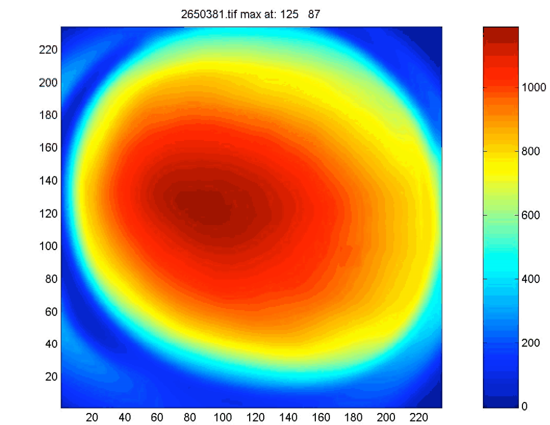
Divergence reduces to 10mrad at high peak power
Characterization & modeling of beams under way

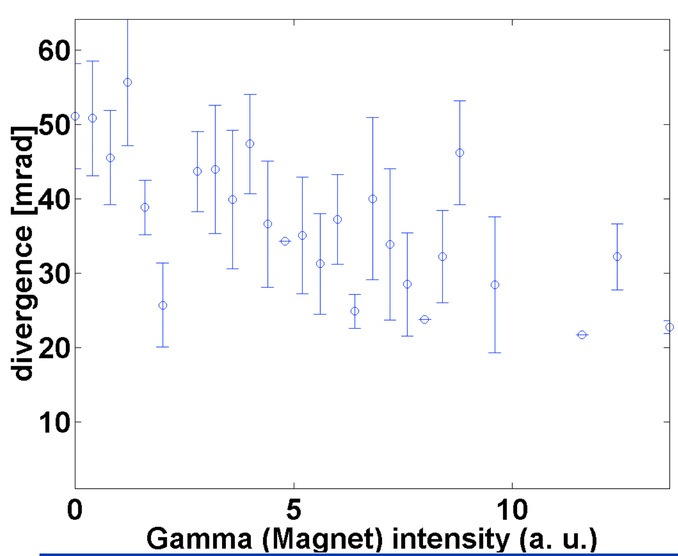


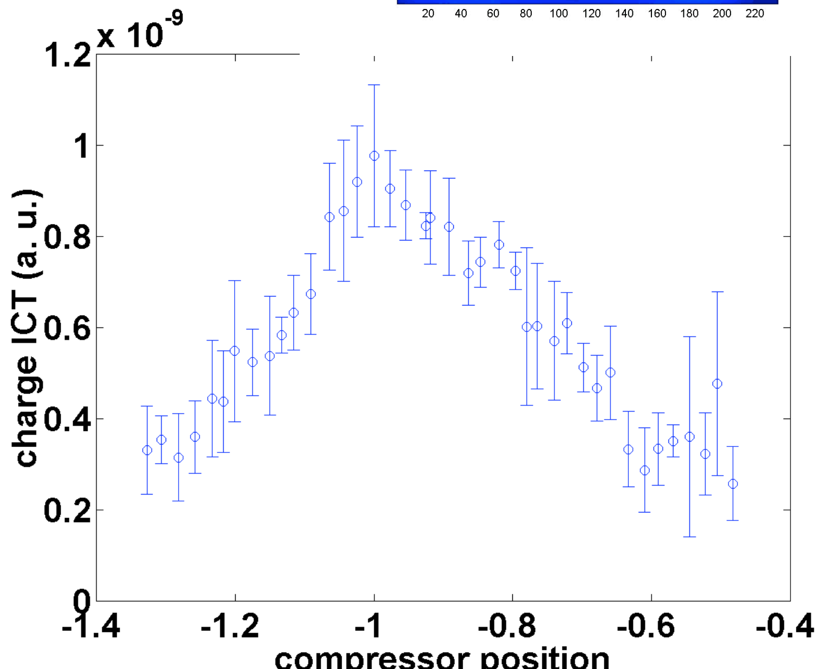
E-beam on phosphor screen, 75 cm away



10 mrad

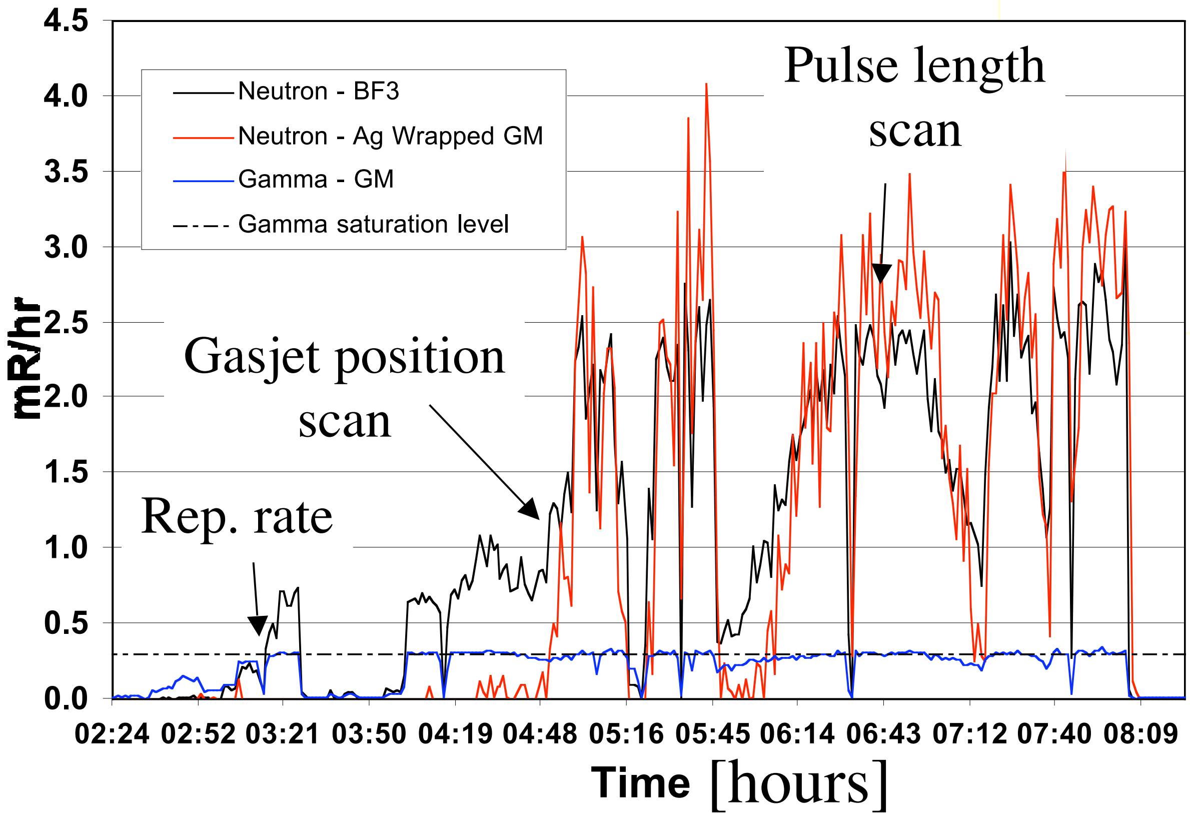


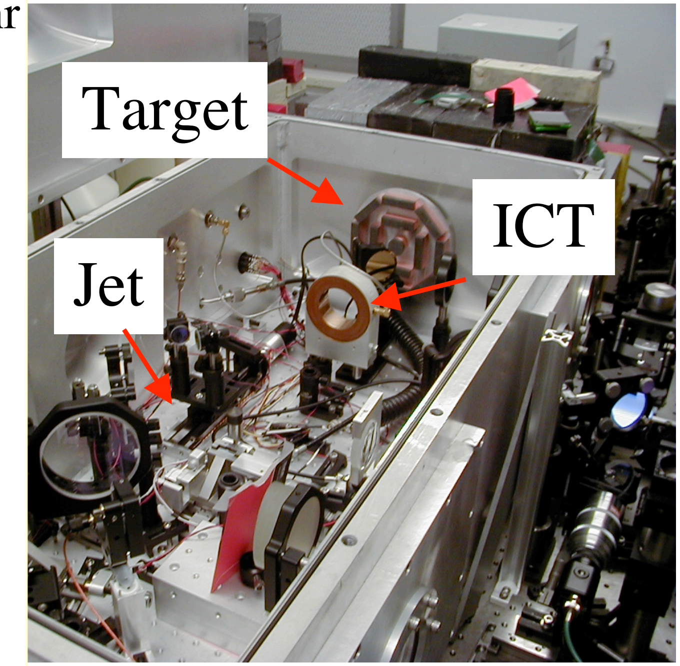




Nuclear activation measurements show electron beam energy >25 MeV and demonstrate radioisotope production

- Observed Cu63 (□,2n) -> Cu61 Cu activity > 0.5 □Ci in< 1/2 hr
  => Beam energy > 25 MeV
- Observed Na^{24} from Al^{27}
  =>(n,□) reaction i.e. >6 MeV neutrons
- Control electron & neutron yield with laser/plasma
- > 3 mR/hr neutron yield





->Beam energy measurement

->Isotope production experiments funded

->need to increase e^- fraction>25MeV

Further Self Modulated Experiments Planned

•steep gradients appear beneficial

•5x increase in gamma ray yield for equal q_{bunch}

•need to

-Better characterize beam:

Magnetic spectrometer & beam phosphor on line.

-Do detailed experiments with sidescatter diagnostic to characterize spot evolution and repeatable laser performance for various nozzles

-Make new nozzles for steeper profiles

-Understand ionization effects: Pre ionized experiments are now possible with multi beam set up.

-model beam propagation to understand effect of different gradients

SDE analytic model (Esarey et al)

WAKE quasi static 3D PIC

Nozzle & Valve Optimization is Important for Accelerator Performance

•Gas jets used in wake field experiments to overcome ionization induced refraction

•Accelerator performance depends critically on jet density, profile, and smoothness as well as on laser focus location in the jet.

•Jet optimization is likely to significantly improve performance.

•Anticipated optimal conditions include:

- -densities of 10^{18} to 10^{19} (achieved)
- -gradient scale lengths of ~ Z_R ~ 100-200um (currently 0.5 - 1mm)
- -density fluctuations < 5% (unknown)
- -cm scale slit jets to allow long L_{int} and colliding pulse
- -faster gas pulses (short on-time allows high rep rate with low pump load)
- -shaped density profiles to escape detuning (long term)

•Jet development efforts include:

- -design and testing of new nozzle shapes (cylindrical and asymmetric)
- -advanced machining to allow production of novel nozzle shapes
- -development of new valve technologies (PZT, micro valves)
- -2w asymmetric imaging interferometer in the accelerator chamber
- -(coming year) modeling of accelerator performance with various profiles

1d Wall Following Perfect Flow Code Allows Fast Modeling of Cylindrical & Rectangular Nozzles

Use the equations of perfect gas flow in a variable area duct derived from assuming isentropic expansion of a perfect gas:

```
T/t0 = 1/((1 + ((□-1)/2)*M^2))
P/p0= 1/((1 + ((□ -1)/2)*M^2)^(□ /(□ -1)))
rho/rho0=1/((1 + ((□ -1)/2)*M^2)^(1/(□ -1)))
A/Astar= (1/M)*( (2/(1+ □)) * (1+((□ -1)/2)*M^2) )^((□ +1)/(2*(□ -1)))
```

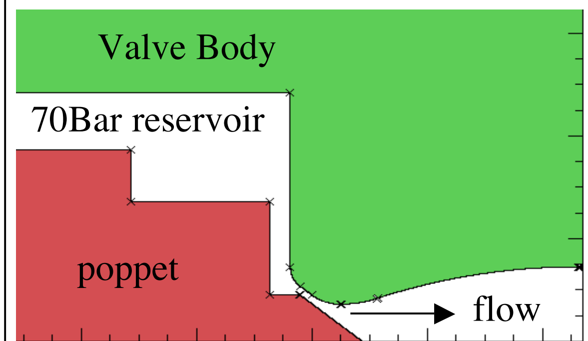
Calculate flow direction at each z location by assuming linear variation of flow angle over cross section & using midpoint.

Allows fast optimization of nozzle shape for smooth mach # contour with cylindrical or slit valves

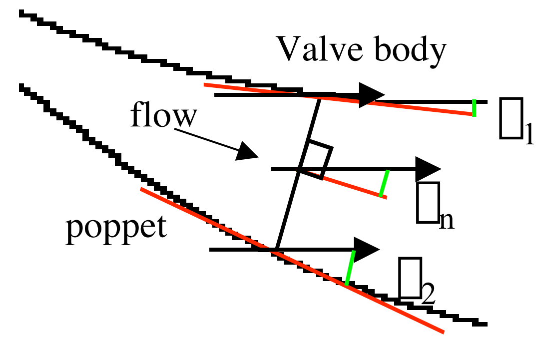
Includes effects of flow direction due to poppet & throat shape.

Geometry export to CMC codes & 3d flow simulations

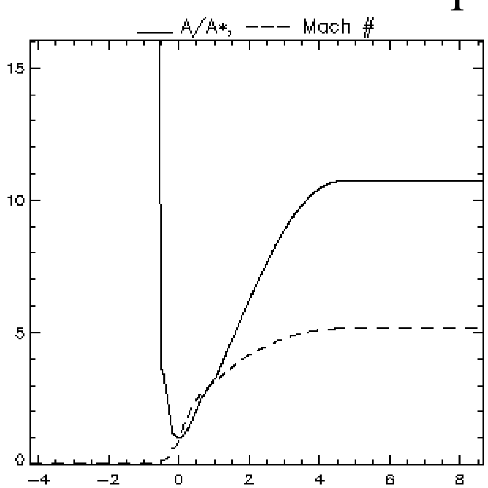
Nozzle Illustration (half)



Code Geometry Illustration



Example Output



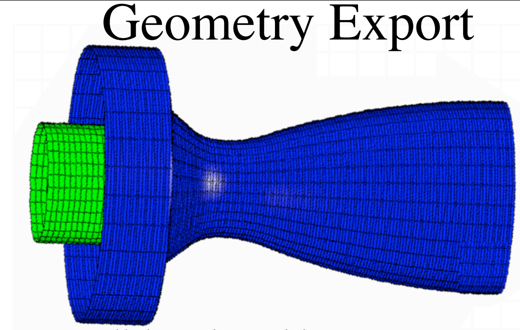
;06- GV bell nozzle redesign
Mon Aug 27 17:20:26 2001

Throat Data:
At=0.619303, Zt=-0.00384712

Opening & poppet data:
opening distance=0.193507, z(open)=-0.00384712
poppet area=2.56647, flow area at opening=0.619303
M at opening=1.00001, Max pressure=77.9281

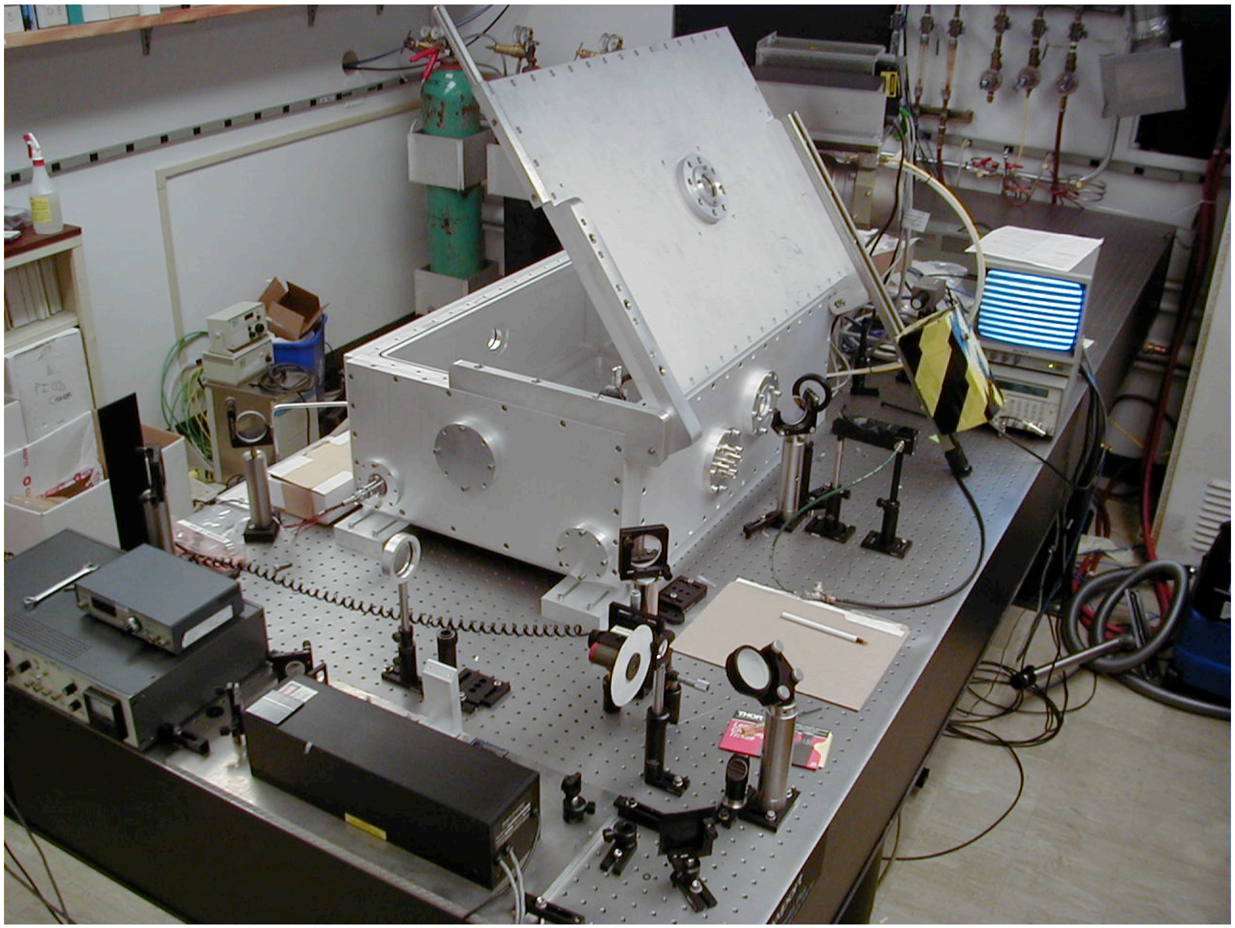
Outflow Data:
Ae/A*=10.7017 Ae=6.62758, Re=1.45248
Me=5.14001, RhomaxE=1.33768e+20, RhoE/rho0=0.0317880

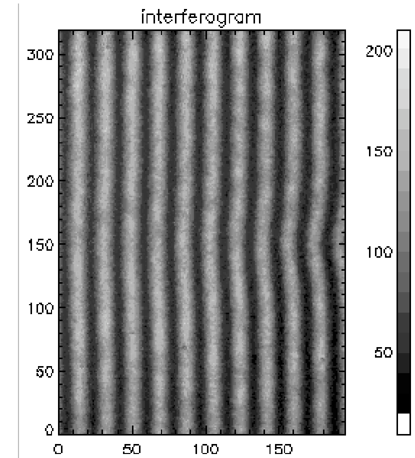
Geometry Export

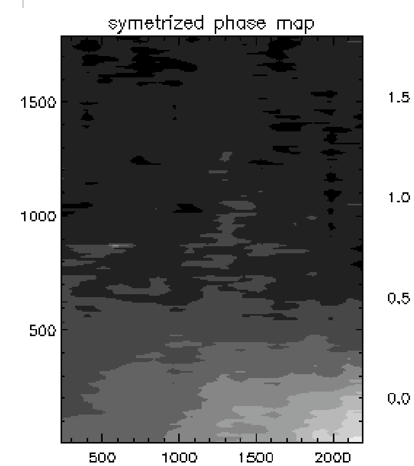


Collaboration with Petersson, LLNL

Test stand with HeNe neutral density interferometer allows fast characterization of nozzles





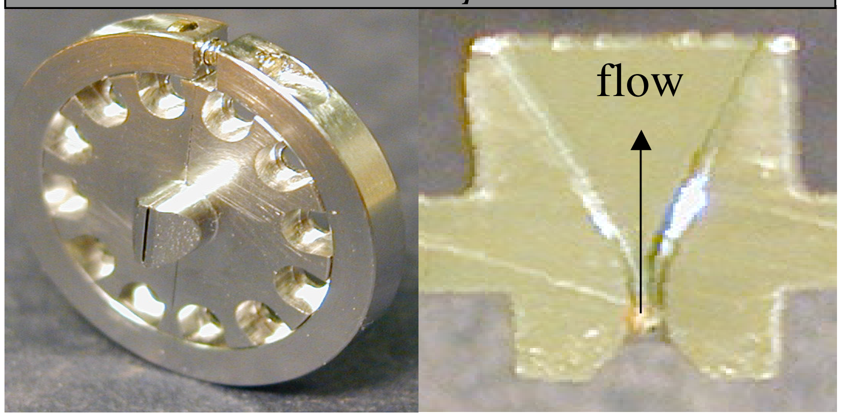


-Neutral density interferometer & fringe tracing recovers 2d phase map with ~0.1rad resolution
-Benchmarked against plasma interferometer
-Testing of nozzles on solenoidal gas jets is under way
-Quick feedback allows rapid iteration of shapes

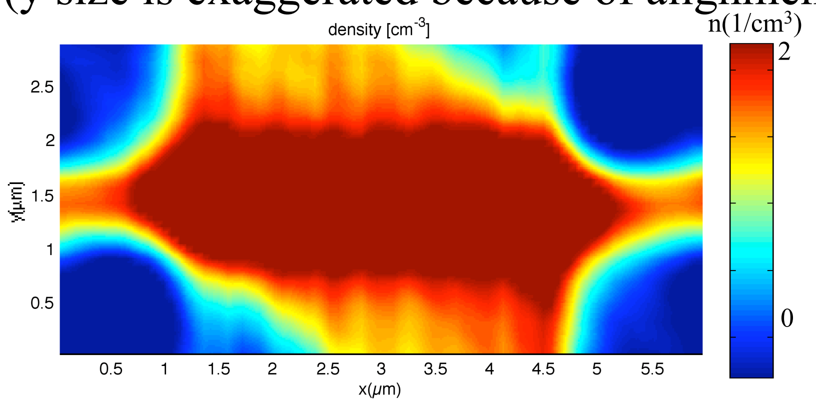
Advanced nozzles and drivers are under development

- Slit nozzles not possible with traditional techniques made using computer machining
- Important for injection experiments

Slit Nozzle 200μm x 4mm

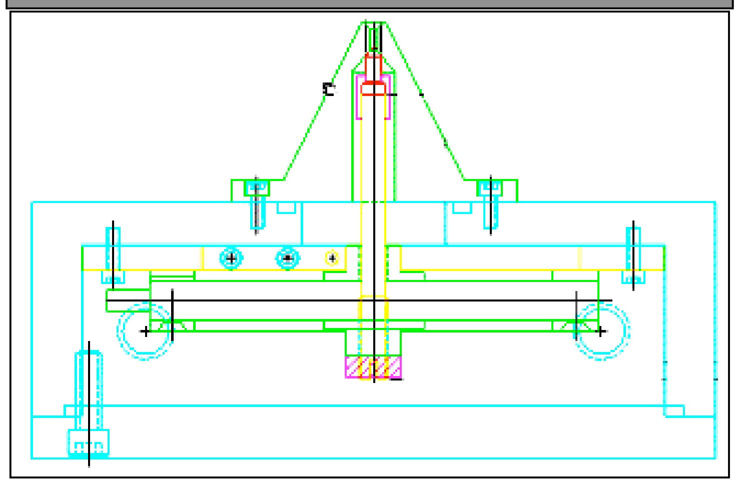


Preliminary Density 1mm from nozzle
(y size is exaggerated because of alignment)



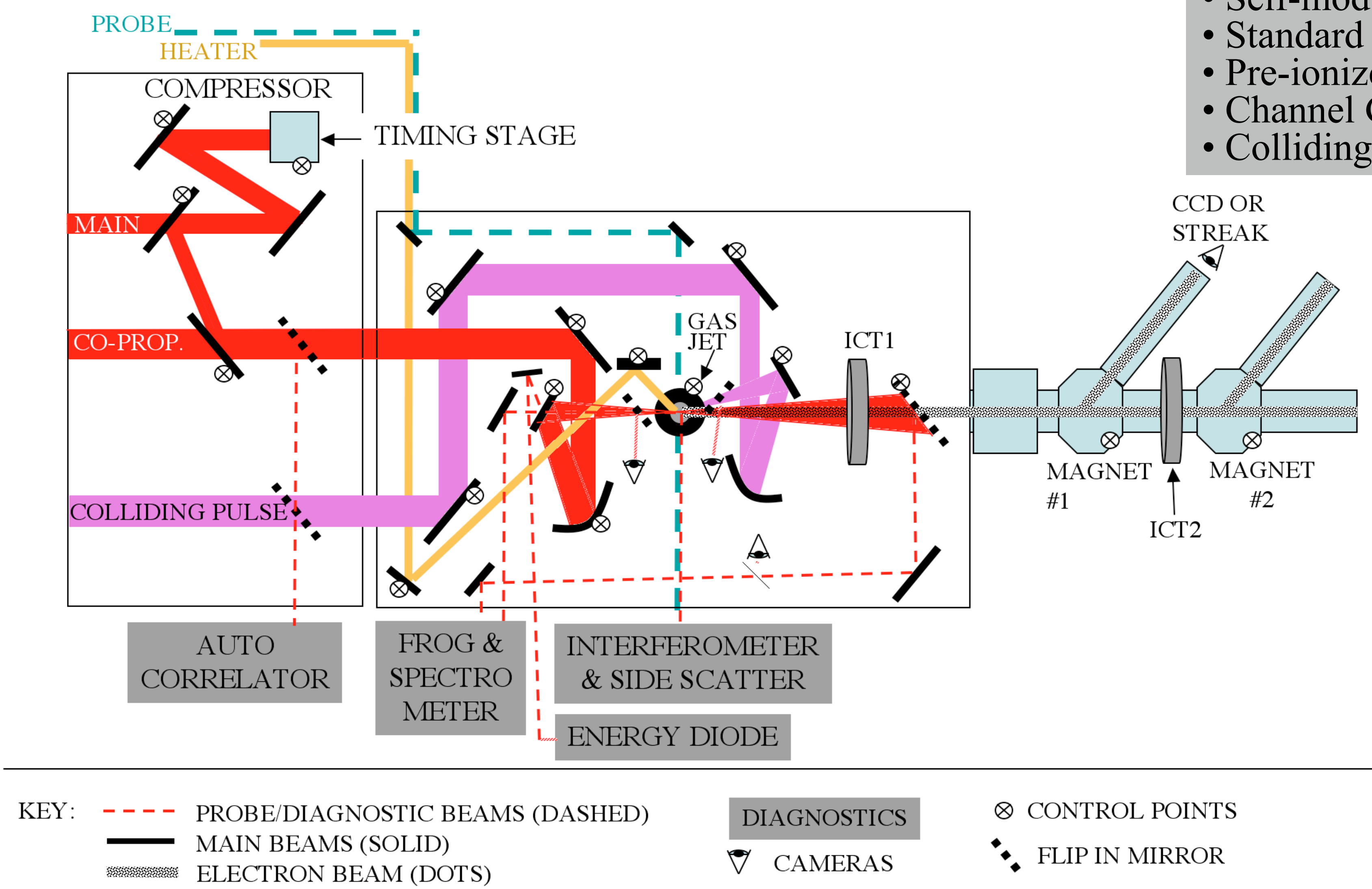
- PZT driven valve built and being tested.
- Faster response & greater force than solenoid valves
- Higher rep rate, lower pump loads, and larger opening areas for long jets.

Piezo Valve

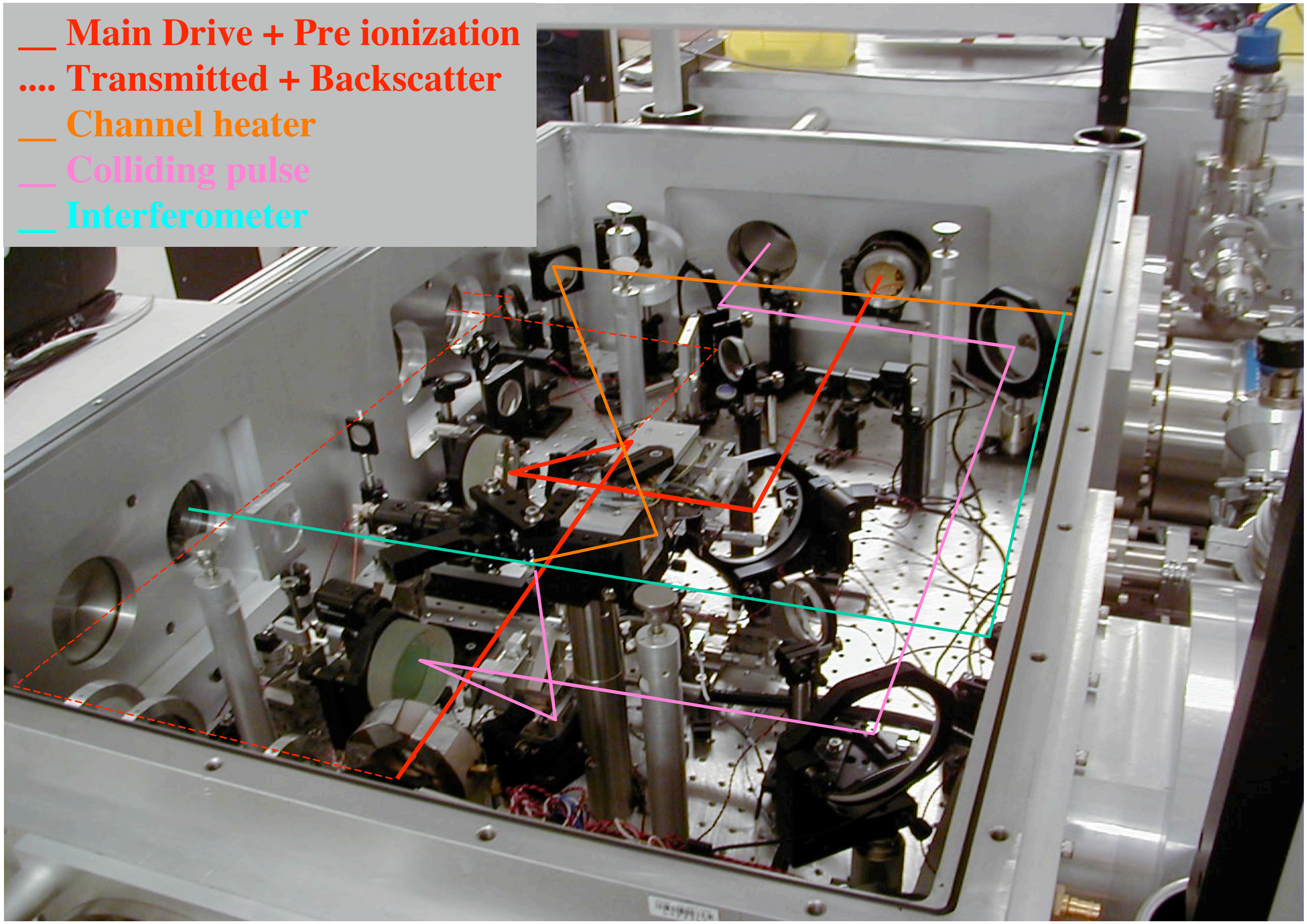


Target area and laser bay have been upgraded to accommodate multiple beam experiments

Experiments:
- Self-modulated
- Standard LWFA
- Pre-ionized
- Channel Guide
- Colliding pulse



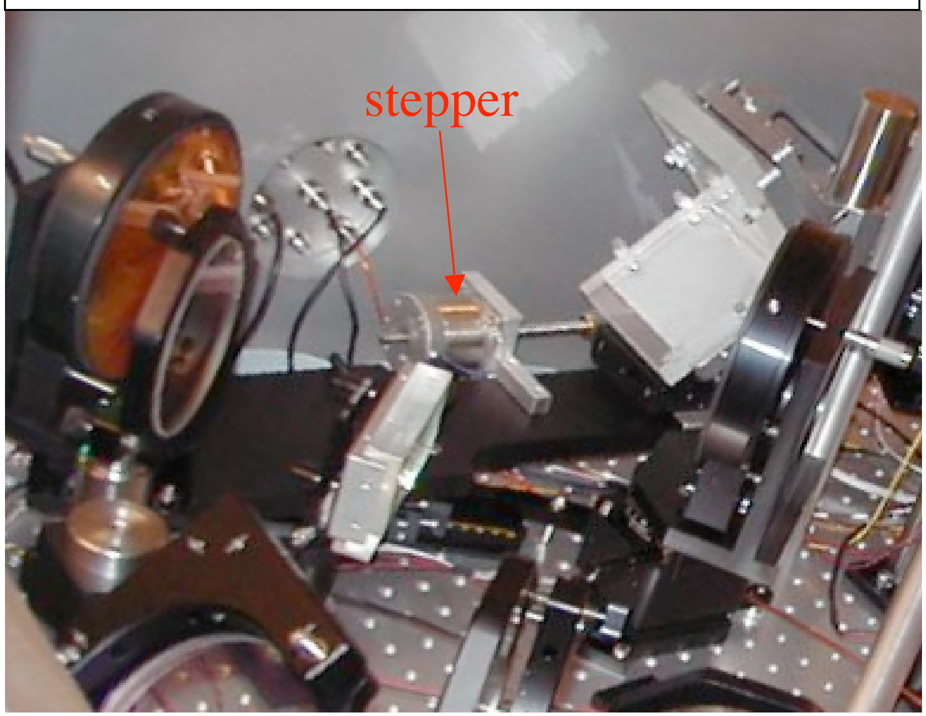
Target area and laser bay have been upgraded to accommodate multiple beam experiments



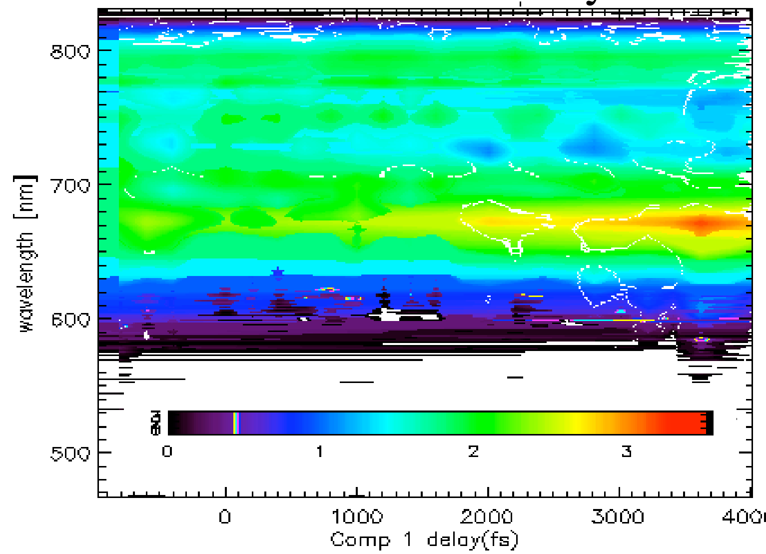
Timing system has been installed

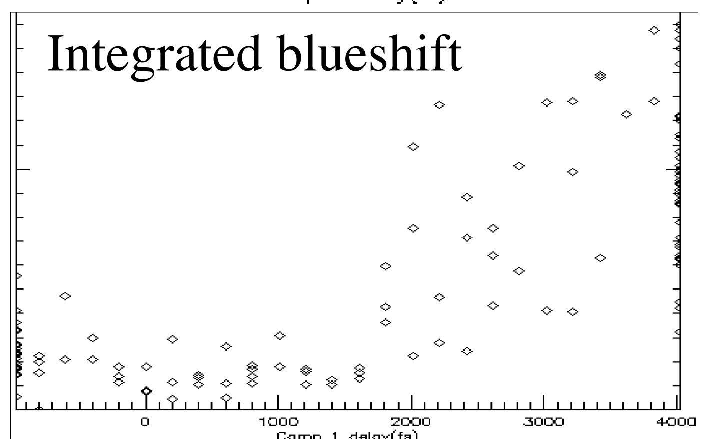
•Beam timing remotely adjustable with fs precision using stepper motors & remote control system
•Allows sychronization of multi beam experiments
•Compressor movement automatically compensated
•Need to characterize stability

Delay stages on Compressors



Measurement of Blue Shift
of Beam0 in Plasma made by Beam1
versus Beam 1 delay





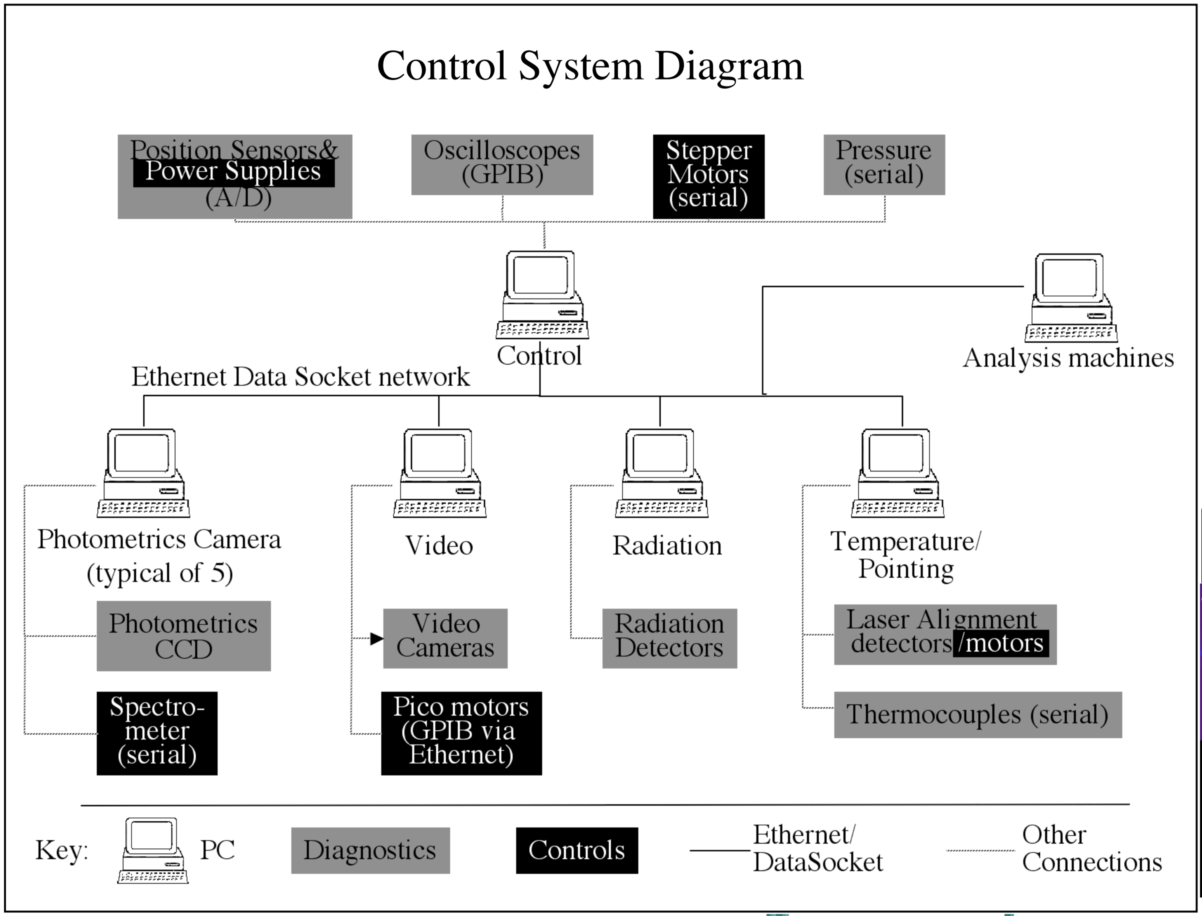
Network based control for the l'OASIS accelerator allows collection of correlated data from diagnostics

-Experiments require collection of synchronous data at Hz rep rates

-A central control system has been implemented that uses low cost IP networking

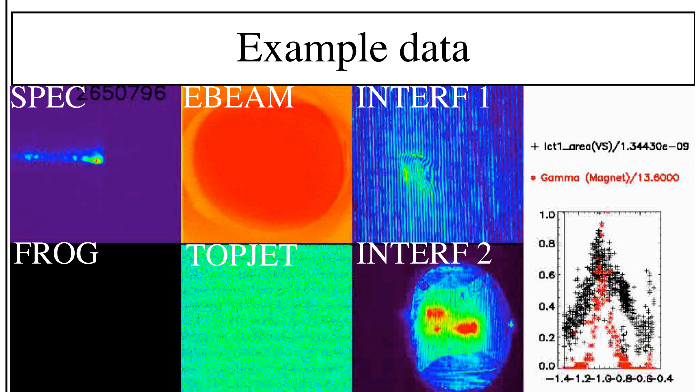
-Sets up many remote machines and diagnostics for each shot, then saves the data

-Data is distributed on the network for viewing



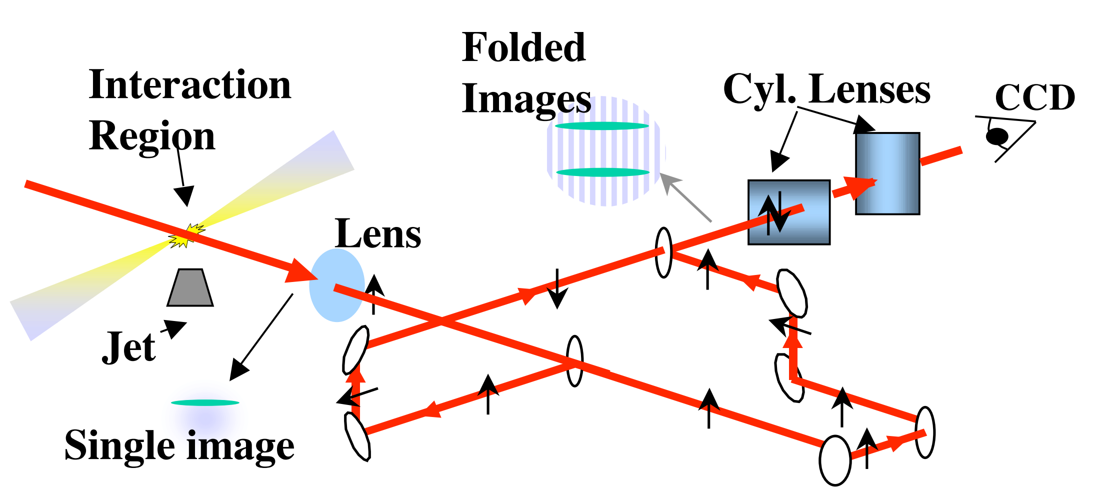
-Controls include:

- -magnet current
- -beam timing, pointing
- -jet position
- -compressor position



Asymmetric imaging camera and 2□ interferometer measure plasma during system shots, separates sidescatter

Interferometer Setup



•Interferometer upgrade has been fielded on accelerator and is taking first data.

•1.4mm * 7mm asymmetric field of view allows imaging of long thin plasma channels

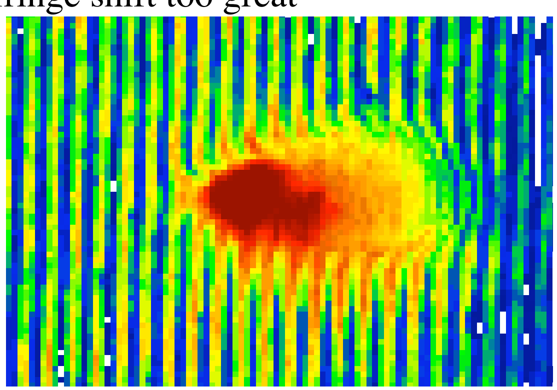
•Allows measurements of plasma at full system energy -> actual shot conditions

1□ Symmetric imaging :500 mJ

-sidescatter contaminates interferogram

-insufficient resolution

-fringe shift too great

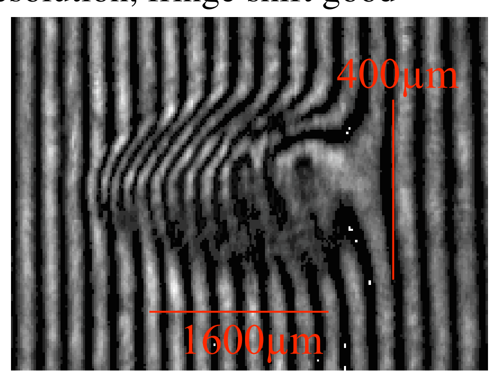


First images: Asymmetric 2□ interferometer

Partial interferogram: 500mJ

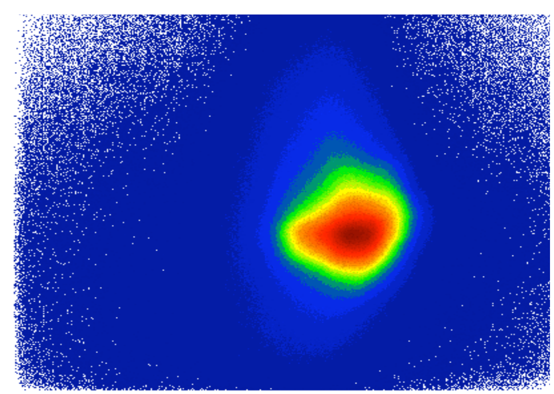
-sidescatter tolerable even at high power

-resolution, fringe shift good



Side Scatter isolated:50mJ

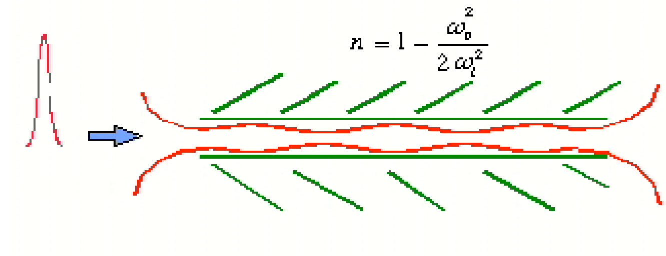
-Separate analysis possible



Laser Guiding Extends Acceleration Region

•Acceleration occurs over distance where laser intensity remains large: ~ Z_R without guiding

•Guiding occurs due to refractive index peaked on axis. For a plasma well below critical density:



$$\eta \approx 1 - \frac{\omega_p^{\ 2}}{2\gamma_{\perp}\omega^2} = 1 - \frac{4\pi e^2 n_e(r)/m}{2(1+a^2)^{1/2}\omega^2} \approx 1 - \frac{\omega_{po}^{\ 2}}{2\omega^2}\left(1 - \frac{a^2}{2} + \frac{\delta n}{n} + \frac{\Delta n}{n}\right) \quad \text{for small a \& } k_p$$

•For pulses ~ λ_p, the wake density perturbation δn cancels the relativistic effect a^2

•Guiding by density channel $\Delta n/n$ is required for short pulses

•Solution of wave equation with parabolic density profile shows gaussian mode of radius r_o for:

$$\eta \approx 1 - \frac{\omega_{po}^{\ 2}}{2\omega^2}\left(1 + \frac{\Delta n r^2}{n r_o^{\ 2}}\right) \qquad \Delta n = \frac{1}{\pi r_e r_o^{\ 2}} \qquad r_{channel} \geq r_o$$

•Tunneling losses can be modeled from WKB theory, coupling from mode overlap.

•Spot evolution for unmatched beams can be modeled by SDE or paraxial wave eqn.

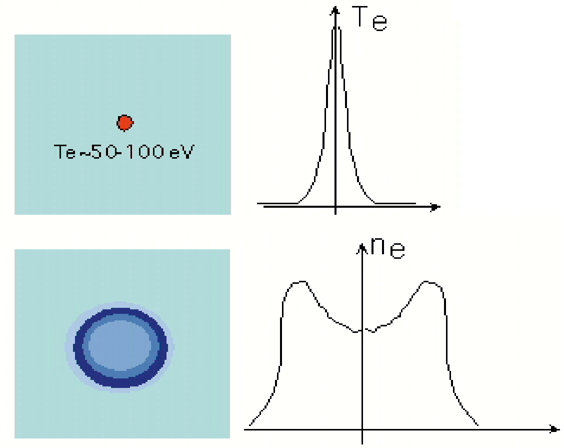
Plasma Channels Guide Laser in Gas Jet Plasmas: Hydrodynamic Ignitor-Heater Method.

Experiments have guided 2 10^{17}/cm^2 over several mm with >50% efficiency using channels formed by hydrodynamic shock*.

Low Z gasses are required for high intensity guiding

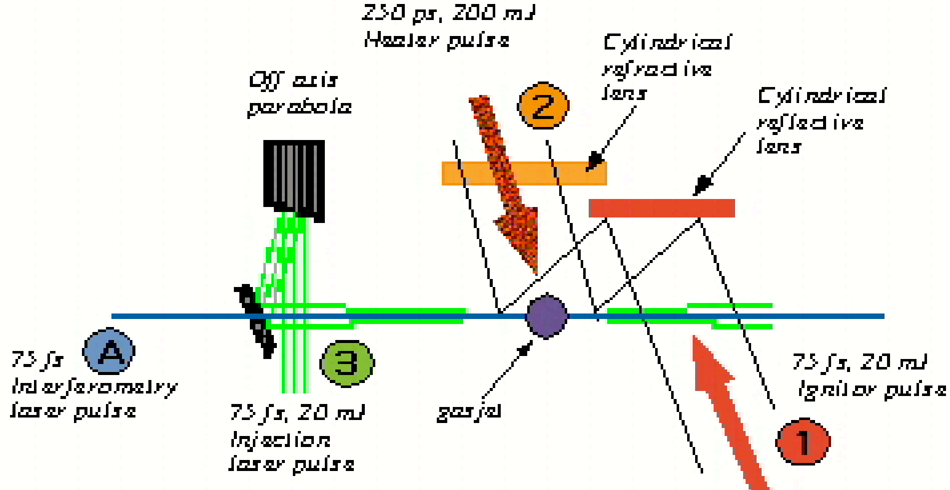
Two pulse formation scheme uses:

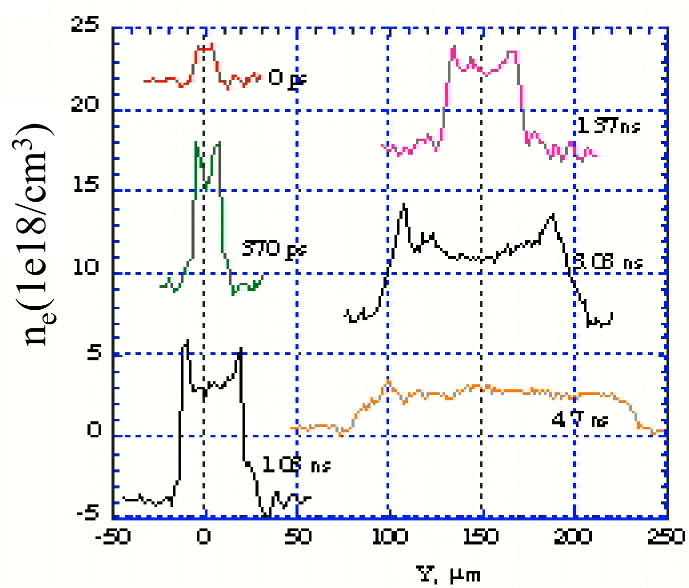
- Ultrashort pulse with I > 10^{14} W/cm^2 for ionization
- 250ps pulse with I ~ 10^{13}W/cm^2 for inverse Bremsstrahlung heating



Future work:

- Extend intensity of guided pulse to > 10^{18}/cm^2 & n_e~10^{18}/cm^3
- Match channel & mode to allow more efficient guiding
- Guide over cm scale distances

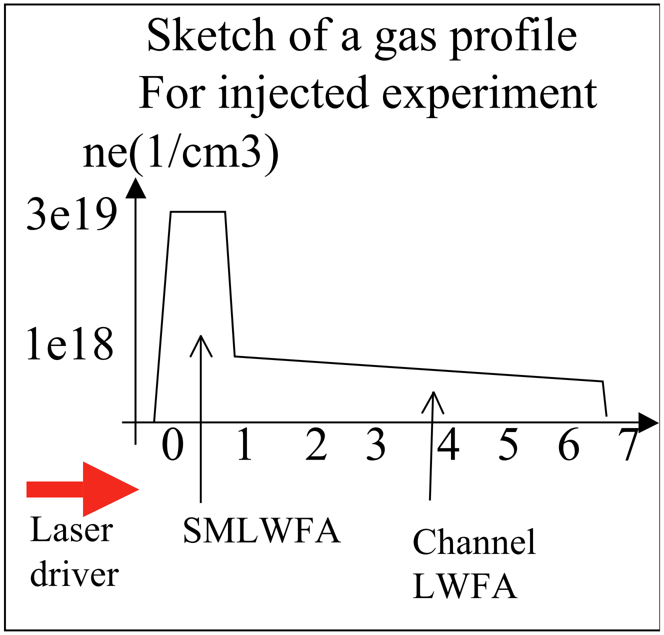




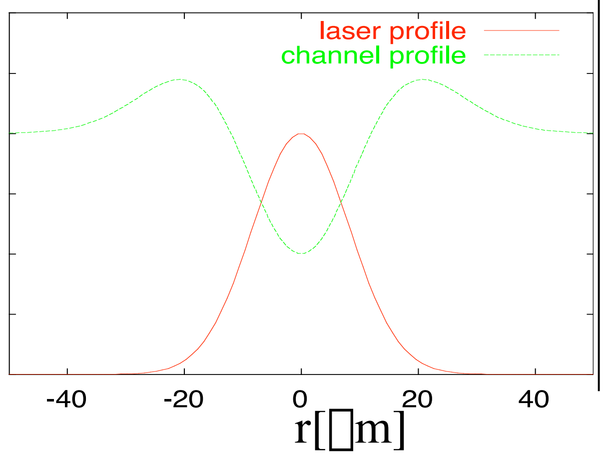
* P. Volfbeyn, MIT Ph.D. Thesis '98
P. Volfbeyn and W.P. Leemans, EPAC 98
P. Volfbeyn, E. Esarey and W.P. Leemans, Phys. Plasmas '99

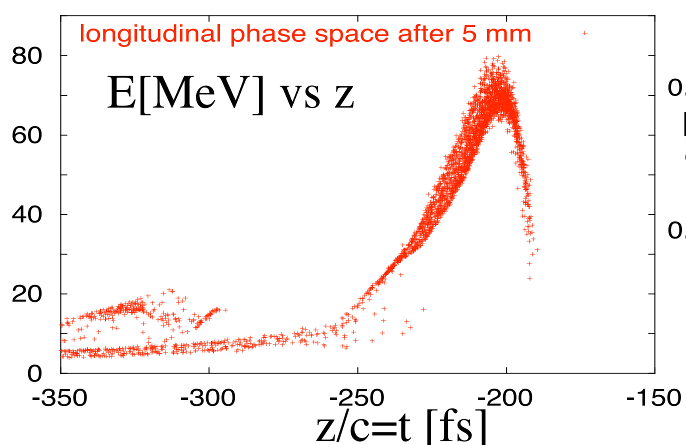
Integrating Self Modulated injector and channel experiments: Expect 10^3-10^4 (γ,n) yield increase

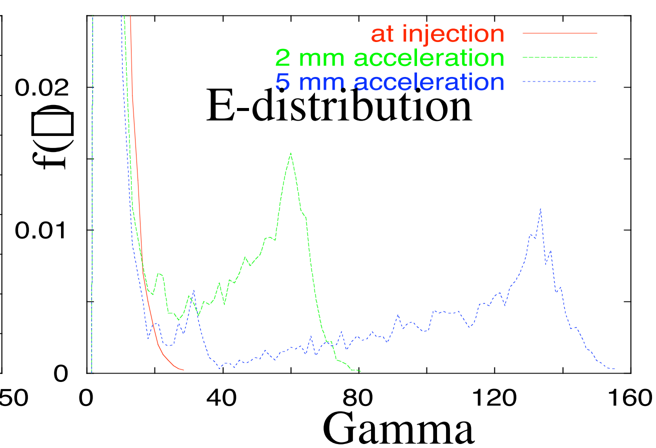
- Non linear fluid code* shows that bunches from a self modulated accelerator can be trapped and accelerated by a channel guided wakefield accelerator
- Simple injection mechanism
- High charge, narrowed distribution: few hundred pC above 30MeV (increase of 10^4)
- Suitable for radio isotope production
- Challenges:
  - -Channel guided accelerator
  - -close coupling to self modulated accelerator
  - -staging using same or separate beams



*Ref: A. Reitsma, et al., PRST-AB,5, 051301 (2002)



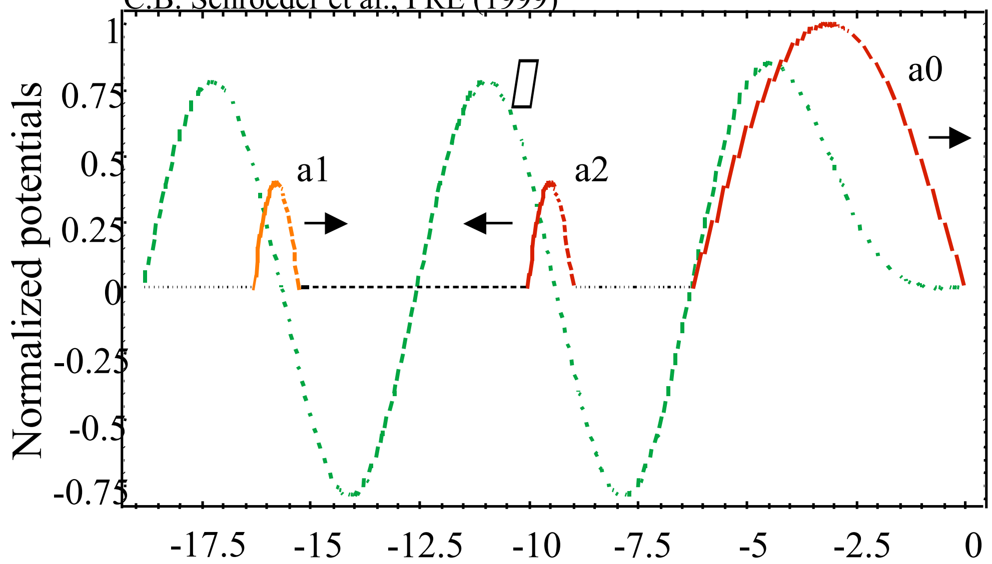




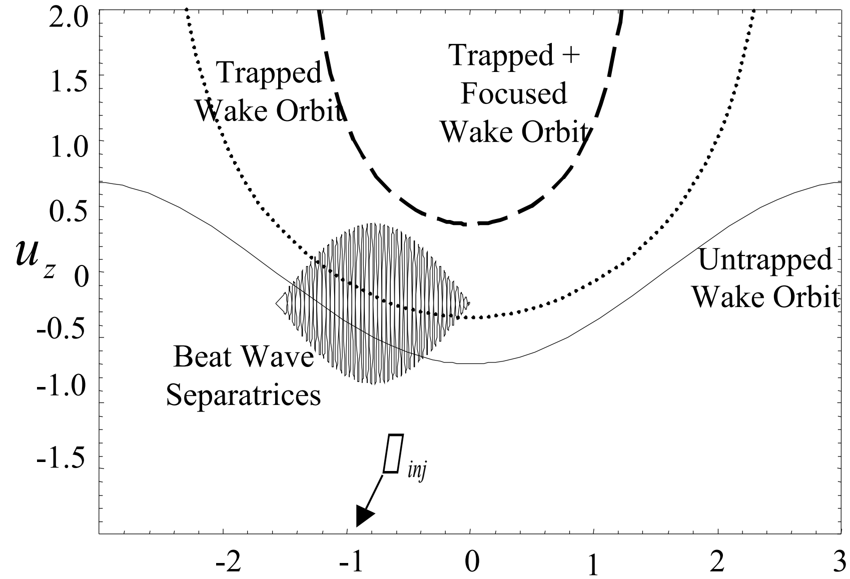
Generation of Ultrashort Electron Bunches: Colliding Laser Pulse Injection Scheme†

†E. Esarey *et al.*, PRL, **79**, 2682 (1997)

C.B. Schroeder et al., PRE (1999)



ψ = plasma wake phase = $k_p z - \omega_p t$



Trapping Mechanism:

I. Pump pulse generates plasma wakefield

II. Injection pulses collide producing a slow beat wave.

III. The slow pondermotive beat wave provides untrapped plasma electrons with a phase shift and momentum gain that allows the electrons to be trapped.

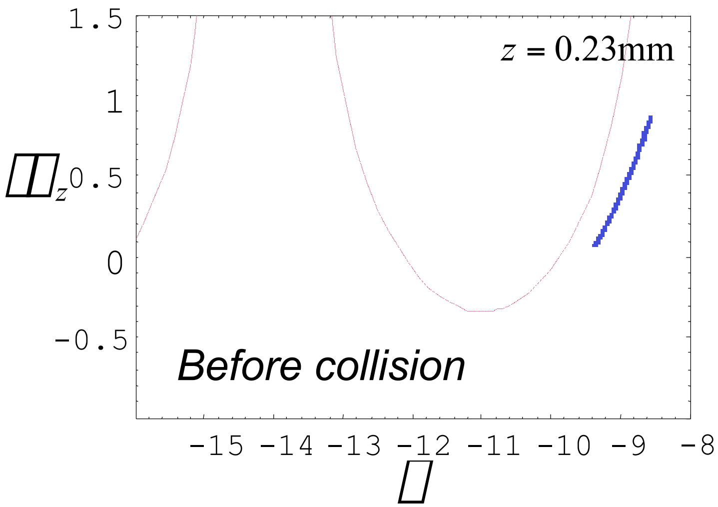
Challenges:

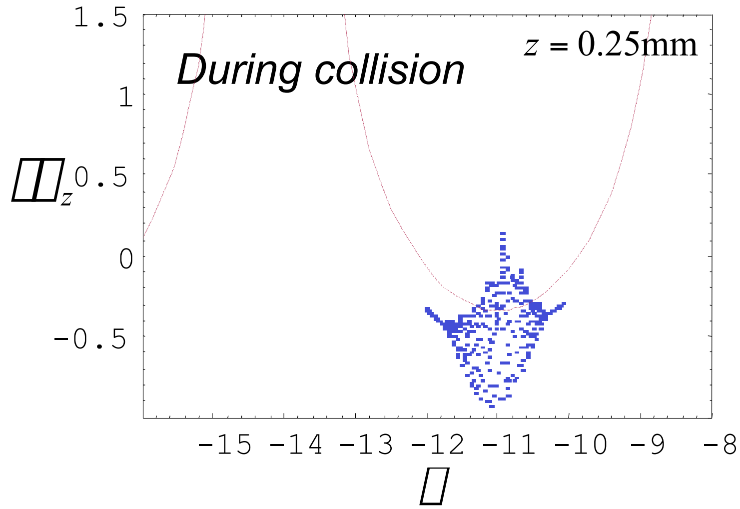
- **channel guiding is required (no self guiding)**
- **timing & pointing of beams**

First experiments use tail of a0 as a1 (2 beams)

Simulations of colliding pulse injector show 1fs, 40MeV beams with < 1% spread

Longitudinal phase space evolution of distribution of plasma electrons

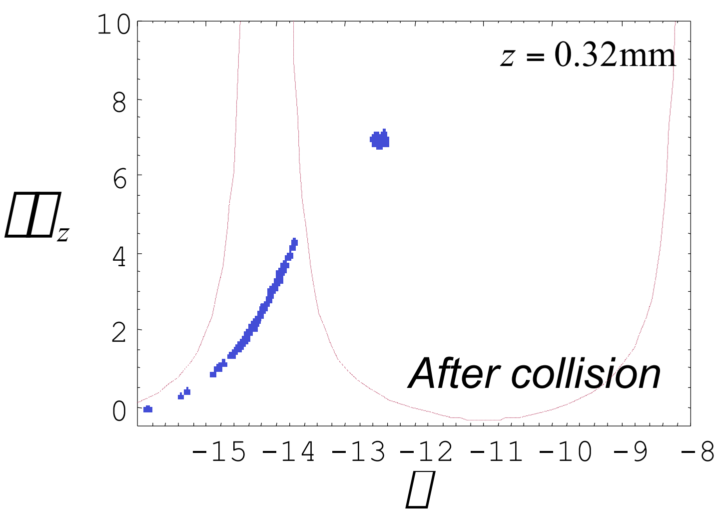




Mean energy = 39 MeV

Bunch duration = 1 fs

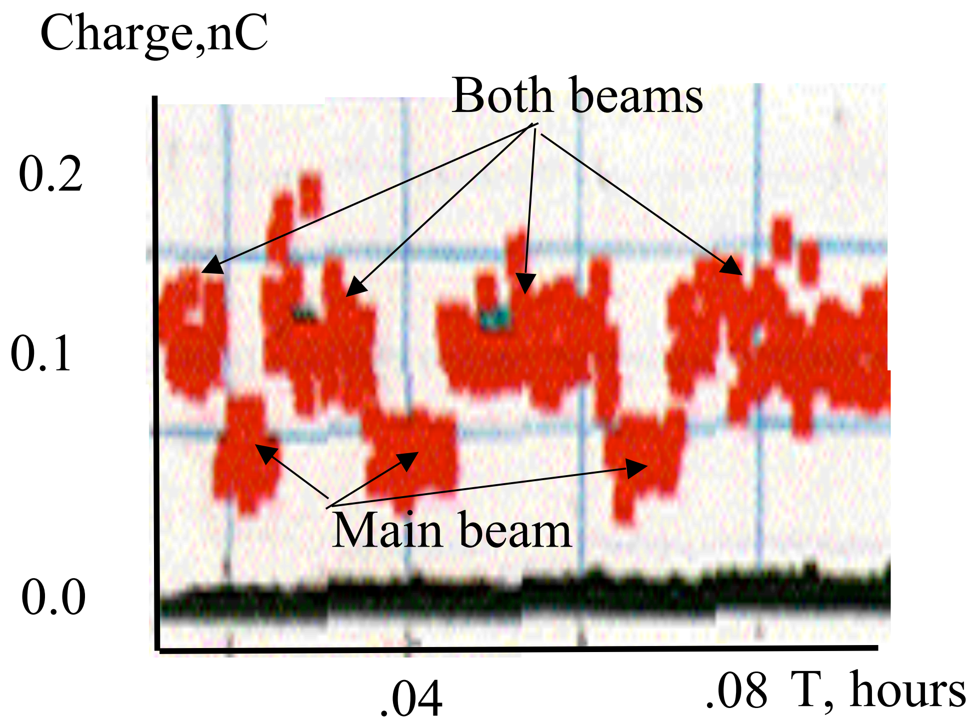
Energy spread = 0.08 MeV



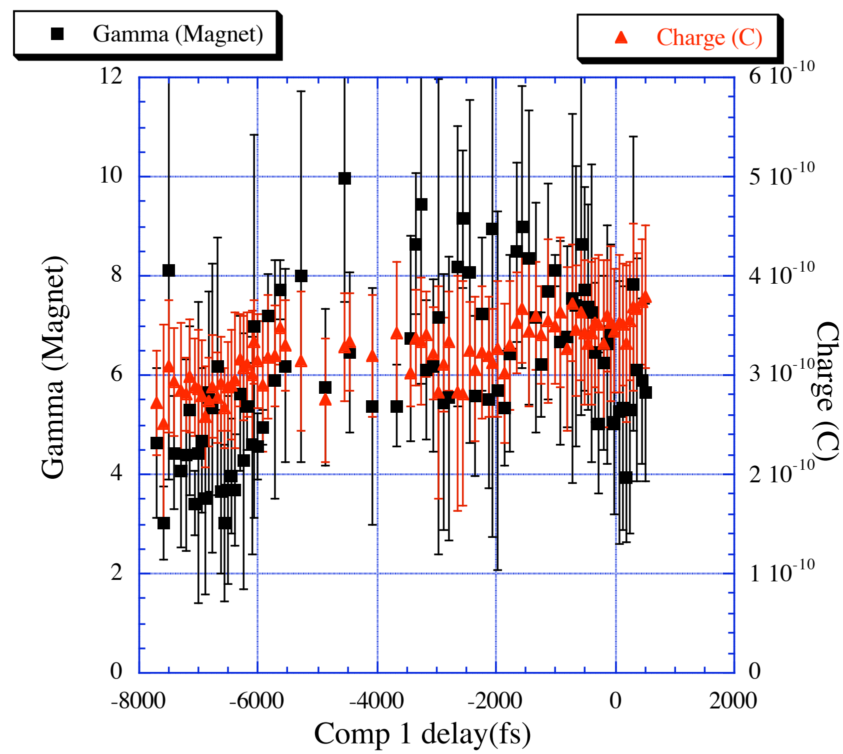
Plasma wavelength	40 μm	(n_o=7x10^{17}cm^{-3})
Pump pulse wavelength	0.8 μm	($\square$= $\square_o/\square_p$ = 50)
Pump pulse length	40μm	
Pump pulse amplitude	~ 0.9	(wake =$\square$ ~ 0.7)
Pump pulse power	5 TW	(spot ~15μm)
Colliding pulse amplitude	~ 0.4	
Colliding pulse length	10μm	
Colliding pulse power	1 TW	
Beat wave phase velocity	-0.2	

Colliding pulse experiments have begun

Enhanced electron yield seen with 'colliding' beam on



Y and Timing scans do not show sensitive dependence
Further alignment needed



Experiments are under way

•Proof of principle experiments are successful
- Self modulated acceleration
- Gas jet development
- Guiding by density channel

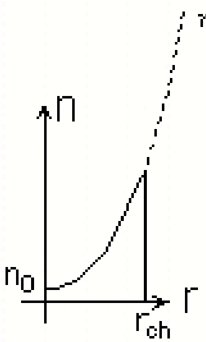
•Experimental systems are on line
- Multi beam interaction chamber
- Multi arm 10 Hz laser
- Control, Data acquisition, and timing system
- Optics in place

Work remaining:
- Further characterize and understand self modulated/guided regime
- Demonstrate laser guiding by density channel at high intensities
- Investigate effect of guiding on acceleration (self modulated & standard)
- Injection experiments:
  - Self modulated to channel
  - Colliding pulse

Laser guiding extends interaction region

$$\hat{E} = \hat{E}_{m,p} L_m^p(\chi) \exp\left[-(1 - i\alpha)\chi/2\right] \cos(p\theta)$$

$$n(r) = n_0 + \Delta n\, r^2/r_0^2 \qquad \chi = 2r^2/r_s^2(z)$$



Source Dependent Expansion of the Paraxial Equation*

$$\frac{d^2 r_s}{dz^2} = \frac{4}{k^2 r_s^3}\left(1 + k r_s^2 B(z)\right)$$

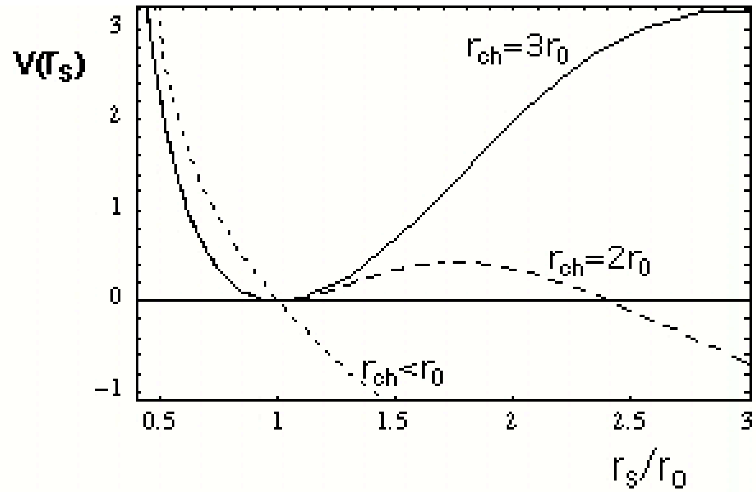
$$B = \frac{m!}{2k(m+p+1)!}\int_0^\infty d\chi\, k_p^2 \chi^p L_m^p L_{m+1}^p \exp(-\chi)$$

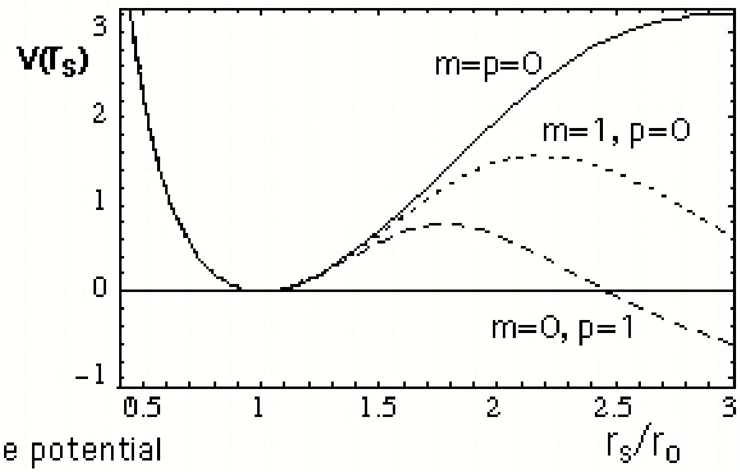
$$B = B_I = -(\Delta n/\Delta n_c)\, r_s^2/k r_0^4$$

Spotsize evolution is a potential well problem

$$d^2 r_s/dz^2 = -\partial V/\partial r_s$$

$$\partial V/\partial r_s = -4/k^2 r_s^3 - 4B/k r_s$$





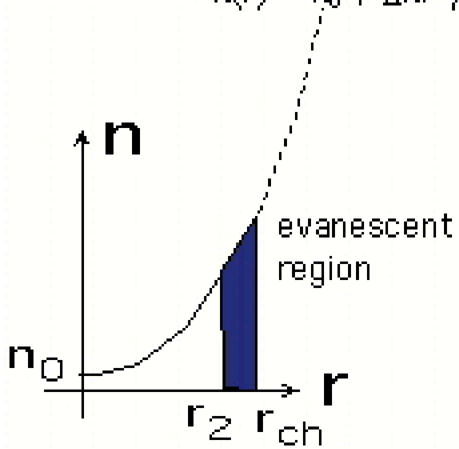
Guiding condition for a beam of $r_s = r_0 = \text{const}$: minimum of the potential

$$\Delta n = \Delta n_c = 1/\pi r_e r_0^2$$

*E. Esarey, J. Krall, and P. Sprangle, Phys. Rev. Lett., vol. 72, pp.2887-2890, 1994

Channel shape determines leakage, higher order mode propagation

$n(r) = n_0 + \Delta n r^2 / r_{ch}^2$



$$(\nabla_r^2 + K^2)E = 0$$

$$K^2 \sim \omega^2/c^2 - k_p^2(r) - k_z^2 - p^2/r^2$$

$$k_z^2 \sim \omega^2/c^2 - k_{p0}^2 - 4(2m + p + 1)/r_0^2.$$

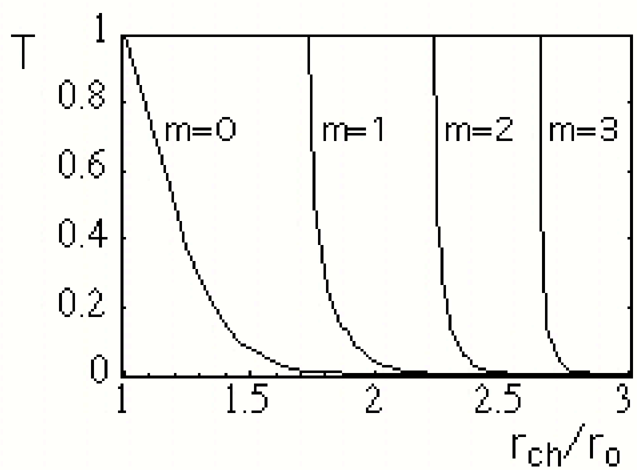
Using WKB tunneling theory*

leakage is $\exp(-\alpha z)$, where $\alpha = T/\Delta Z$ is attenuation coefficient

$$T = \exp\left(-2\int_{r_2}^{r_{ch}} dr(-K^2)^{1/2}\right)$$

$$\Delta Z = 2k_z \int_{r_1}^{r_2} dr(K^2)^{-1/2}$$

For p=0 modes:



*P.K. Cheo, *Fiber Optics: Devices and Systems*, (Prentice Hall, Englewood Cliffs - NJ, 1985).

Trapping of electrons

Only electrons near the velocity of the wake are accelerated for a long distance.

Low speed electrons only oscillate back and forth in the plasma wave potential but are not trapped.

Need a way to trap electrons:

-A injected beam from a photocathode can be used, but this sacrifices high charge/short pulse advantage of laser driven accelerators.

-High enough wake amplitude traps bulk electrons (wave breaking)

-Raman backscatter wave can give electrons a ‘kick’ that can allow them to be trapped - but at random phase, leading to 100% energy spread.

-All optical injection methods have been formulated to inject electrons at controlled phase

l'OASIS 10TW Ti:Al_2O_3 Chirped Pulse laser for wakefield acceleration

- Electron energy gain proportional to power; 10 TW needed for 1GeV.
- Chirped pulse amplification allows compact high power systems.